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Soil Cohesion as Affected by Time and Water Content

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ABSTRACT

Cohesion increased for several months after disruption in moist soils. Rate at which cohesion increased was slower in air-dry soil, but continued for years. Moduli of rupture of soils also increased with time. Effects of water content on the rate at which cohesion increases are compatible with an explanation of the bonding mechanism in terms of slightly soluble components diffusing to and cementing points of contact between particles. Cohesional forces due to water are estimated and found to be large enough to provide a major portion of the cohesion measured in soils. These estimates are supported by decreased cohesion of a silty soil when dried. However, cohesion of soils with larger amounts of clay generally increases when they are dried, indicating that other bonding mechanisms predominate.

Additional Index Words: tilth, aggregate stability, modulus of rupture, cementation, interparticle bonding, soil strength, soil disruption, bonding agents, diffusion.

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THE TENDENCY of soil particles to cohere in aggregates contributes to more open soil structure with larger sized pores and less resistance to rupture than would occur if there were no aggregates. Larger sized pores facilitate air and water entry to the soils and make them a more favorable rooting media for plants. Reduced resistance to rupture facilitates cultivation and seedling emergence. This study was designed to evaluate effects of water content and time on the cohesion of soil and uses the resulting information to help elucidate the mechanisms involved in cohesion.

PROCEDURE

Soil samples were taken from Portneuf soils (southern Idaho) in 1972, sieved through a 2-mm screen, and air dried. Additional samples were taken from the same location and treated in the same way in 1983. Samples were also taken from the Billings series in the Grand Valley of Colorado and treated in this same manner in 1982. The Portneuf soil is wind deposited with over 60% silt and < 20% clay. The Billings soil is alluvial, with less silt and more clay and is more cohesive and less susceptible to erosion.

Aggregates in the 1- to 2-mm size range were separated from these samples by sieving. After the storage times indicated in the figures and text, aggregates were moistened to 0.04 to 0.30 kg H₂O kg⁻¹ soil by placing them on screens and passing air containing water droplets < 0.1 mm in diam through the aggregates for times ranging from 50 to 100 min (Kemper and Rosenau, 1985). Water contents lower than 0.028 kg kg⁻¹ were achieved prior to aggregate stability determinations by placing air-dry samples over P₂O₅ in desiccators. Water contents of a portion of these aggregates were determined by weighing, oven drying, and weighing again.

Aggregate stability of duplicate samples with the indicated water contents were determined by immersing them at at-

mospheric air pressure and sieving them in water, using the procedure by Kemper and Rosenau (1985). The percent of the soil particles smaller than 0.25 mm which do not go through that size screen during the sieving is the aggregate stability in Fig. 2.

Water retention was determined on duplicate soil samples from 1 to 1500 kPa using pressure-extraction cells. Air-dry samples of < 2-mm soil aggregates and particles were compacted at about 60 kPa into short lucite rings on the pressure plates and allowed to absorb water by capillarity in preparation for retention measurements. The retentions at 10 000 kPa were determined by placing duplicate moistened samples in a desiccator where the relative humidity was maintained at 92% relative humidity and weighing daily until weight was constant.

Moduli of rupture were determined on soil cylinders using the procedure outlined by Kirkham et al. (1959). Lucite rings, 5 cm tall and 2.5 cm i.d., with aluminum foil inner liners, were set on filter paper in pans. Duplicate samples of air-dry soils were compacted into these rings with 60 kPa of uniaxial mechanical pressure. The soils were moistened by filling the pans with water to a depth of about 4.5 cm. After about 1 h, the free water was removed from the pans. The rings were then laid on their sides exposing both ends to the laboratory atmosphere and allowed to dry slowly. They were weighed daily to determine water contents. When the soils reached the desired water contents they were removed from the lucite rings and their moduli of rupture were determined by pressing them between two plates with increasing force until the soil cylinder broke. The details of the apparatus used are given by Kemper et al. (1975). In some cases the cylinders of soil at the desired water contents were "cured" by storing them in sealed pint jars for 2 weeks prior to determining their moduli of rupture.

RESULTS AND DISCUSSION

Water retention characteristics of the Portneuf and Billings soils are shown in Fig. 1. Aggregate stabilities (wet sieve method) of Portneuf soil, with the indicated initial water contents, are plotted in Fig. 2. The standard error of determination for the aggregate stability measurements in this study was 1.7%. The bottom curve indicates the stabilities determined 2 weeks after the 1983 sample was taken, sieved while moist, and air dried. In general the aggregate stability increased as the sample was stored in an air-dry condition in the laboratory. After the second week (3 February) the

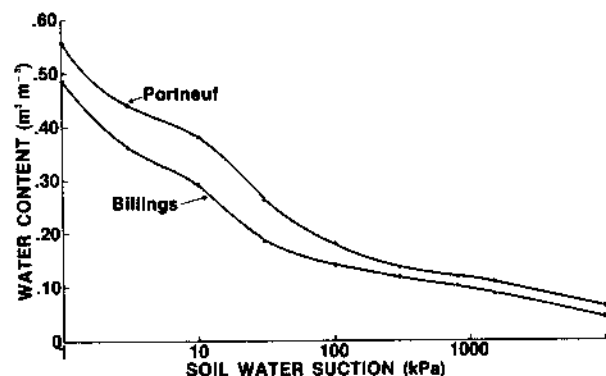


Fig. 1—Water retention curves for Portneuf and Billings soils.

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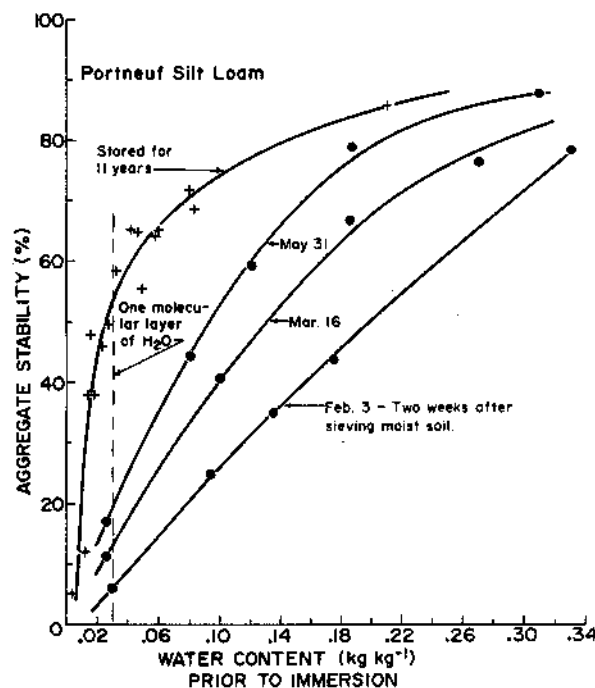


Fig. 2—Aggregate stability as affected by air-dry storage time and water content immediately prior to immersion.

sample in storage had a water content of about 0.03 kg kg^{-1} , which was equivalent to about one molecular layer of water on all the surfaces. By 31 May, this water content was 0.026 kg kg^{-1} . The soil sample which had been stored for 11 yr had a water content of about 0.025 kg kg^{-1} . The stabilities of these aggregates, stored for 11 yr (top curve of Fig. 2) were high.

In general, the disruptive forces caused by wetting the aggregates are larger when the water content prior to immersion is lower. Moistening the samples to a range of water contents prior to immersion provides a range of disruptive forces. Measured differences in stability of these samples were small when the initial water contents approached zero or were above 0.30 kg kg^{-1} . However, when water contents, prior to immersion were in the range from 0.03 to 0.20 kg kg^{-1} , differences in stability were easily discernible.

The disruptive forces of wetting, including differential swelling and escape of entrapped compressed air, reduce the stability of Portneuf soil to practically zero when oven-dried aggregates on the sieves are immersed in water. Slower wetting avoids entrapment of air and reduces spatial swelling differences leaving a larger portion of the particles cohering in the aggregates. Disintegration of the aggregates into micro-aggregates and primary particles allows the particles to settle into closer packed and more highly interleaved configurations, which on drying would be expected to have higher moduli of rupture.

Consequently, prior to determinations of modulus of rupture, some samples were wetted quickly by the procedure described in the previous section, and others were wetted slowly by slowly moistening the filter paper under the rings. By the latter procedure the time of wetting could be extended as long as desired. However, the hydraulic conductivity of the soil places an upper limit on the rate of wetting. The shortest wetting

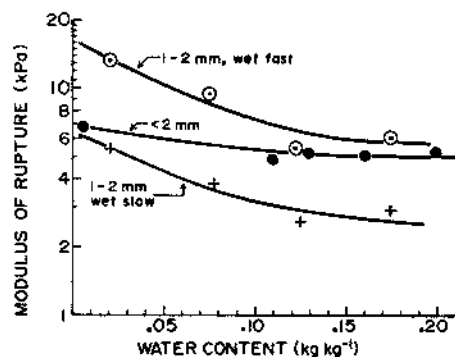


Fig. 3—Modulus of rupture of Portneuf soil as affected by rate of wetting.

time achieved was about 4 min. Moduli of rupture of soil cylinders wetted in 4 min were slightly greater than of those wetted in 4 h, but the differences were small and both fell near the middle line shown in Fig. 3. The average coefficient of variation of the means of the duplicate samples on which modulus of rupture was determined in this study was 5.6%.

To achieve a more rapid rate of wetting, the aggregates and primary particles $<1 \text{ mm}$ in diam were removed from the $<2\text{-mm}$ size range and the remaining $1\text{-to } 2\text{-mm}$ aggregates were used to fill the rings. When soil cylinders of this material were wet slowly, their moduli of rupture were considerably lower (bottom curve of Fig. 3), than those of the samples which included the $<1\text{-mm}$ size fraction (middle curve). However, when these $1\text{-to } 2\text{-mm}$ aggregates were wet by quickly bringing the water level in the pan to near to the tops of the rings, the whole sample was wet within 1 min. This faster rate of wetting resulted in more disintegration of aggregates and interleaving of particles and a greater cohesion as indicated in the top curve of Fig. 3. However, wetting the 5 cm tall sample during a period of 1 min is still not as rapid wetting as the direct immersion of aggregates on a sieve as was done in the aggregate stability determination. Remnants of the original aggregates and associated larger pore space were still apparent in the broken faces of the ruptured cylinders. Exposure of the surface layer of soils in associated studies in irrigation furrows and bordered strips to immediate wetting was found to be a major factor in their subsequent high density and crust strength.

An increase in cohesive strength due to curing or time of storage is also indicated by the moduli of rupture values. The line shown in Fig. 4 associated with the upright crosses represents samples "cured" for 2 weeks after reaching the indicated water contents, before rupturing. This line is appreciably above the line associated with the diagonal crosses which represent cylinders which were not "cured" prior to rupture. In a study to be published in another journal, the authors noted similar increases in moduli of rupture with aging of the Billings soil.

A characteristic of this Portneuf sample that was different from the Billings, and probably from most other soils, was its decrease in modulus of rupture when it was oven dried. This difference (open circles vs. upright cross data points in Fig. 4) indicates that at least a major portion of the cohesion of this soil as

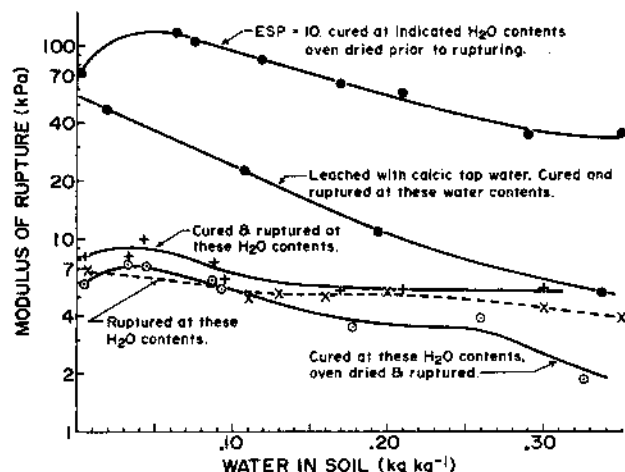


Fig. 4—Moduli of rupture of Portneuf soil following various pre-treatments.

measured by resistance to rupture, was associated with presence of the water.

The Billings soil had moduli of rupture that were several times higher than those of the Portneuf when the soils had water contents $< 6\%$ (Fig. 5), but at water contents $> 20\%$ more force was required to break cylinders of Portneuf than of Billings soils.

The Billings had about 3% Na in its exchange capacity while the Portneuf had practically no Na. To compare the moduli of rupture at the same low exchangeable Na levels, samples of the Portneuf and the Billings soils were leached with 20 pore volumes of calcic tap water. Samples of Portneuf soil were leached with a mixture of Na and Ca chlorides which would give exchangeable Na levels of 10%. These samples were then air dried, passed through a 2-mm sieve, and used to form cylinders for modulus of rupture determinations as before. The results for the Portneuf soil are shown as the top two lines in Fig. 4. The 10% exchangeable Na soil had the highest moduli of rupture because the aggregates dispersed in the water with low salt content which was used to wet the cylinders. However, the moduli of rupture also increased appreciably for both the Portneuf and Billings soils which were leached with 20 pore volumes of calcic tap water (Fig. 5) in spite of the fact that this leaching had lowered the exchangeable Na level of the Billings from 3% to $< 1\%$. The crossing of the moduli of rupture curves, noted in soils with their original ionic complement, was just as definite for the soils leached with calcic tap water. This indicates different types of binding forces in the two soils.

A possible explanation of the different behavior of these two soils lies in their different textures. The Portneuf has 15% clay whereas the Billings has over 40% clay. The clays are largely smectites whose individual platelets are so thin that they can be bent by small forces. When pulled together by moderate tensions in the water, the larger, blockier silt particles of the Portneuf are probably forced into contact at a limited number of contact points and bonds begin developing at those points. The Billings, with more clay, has more interfacing of clay particles, but the osmotic swelling pressures may be sufficient to prevent most of these

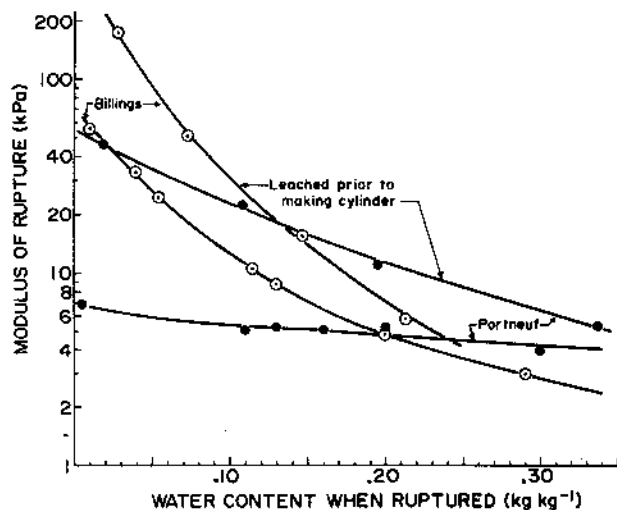


Fig. 5—Modulus of rupture as affected by leaching with tapwater prior to forming cylinders.

clay platelets from making solid-to-solid contacts, particularly since the thin platelets may deform in response to high osmotic pressures, leaving cushioning films of water between the solid surfaces. However, when the tensions in the water increase, more of these clay particles begin to make contact and bond and ultimately, since there are more contacts, there is greater cohesion in the clayey than in the silty soil when they are dry.

The suggested need for both mineral-to-mineral contact and subsequent migration of bonding agents to those points of contact is compatible with findings of Utomo and Dexter (1981b) that rates at which soils harden are greatest at intermediate water contents, characteristic of the soils, and decrease when the soils are wetter or dryer.

The long-term leaching process followed by air drying and fragmentation resulted in new aggregates. The internal cohesion of these new aggregates is not as great as that of the older ones. Consequently, when they were wetted again in the lucite rings there was more disintegration of the aggregates and greater coalescence of the soil into one large mass which has more resistance to rupture. Greater stability of aged compared to new formed aggregates has also been noted by Utomo and Dexter (1981a). Their new aggregates were formed by tillage of a moist soil which was then sieved through a screen. Effects of aging the aggregates on aggregate stability were similar. They also found that aging aggregates prior to compression substantially decreased their packing density, indicating increased cohesiveness of particles in the aggregates.

Blake and Gilman (1970) also noted increased aggregate stability of fragments from newly compressed briquets when these were stored at constant water contents. In their studies, when the water contents were high (i.e., $\theta = 0.31 \text{ m}^3 \text{ m}^{-3}$), maximum stability appeared to be reached within a day, whereas at lower water contents ($0.16 < \theta < 0.24 \text{ m}^3 \text{ m}^{-3}$) stabilities were still increasing after several days. The effect of water content during storage on rate of cohesion development is confounded in their studies with the ef-

fect of water content immediately prior to immersion on the disintegrating force during the wet sieve stability determination. As indicated in Fig. 2, forces disrupting aggregates are strong when those aggregates are dry before immersion, but are minimal when the aggregates have high water contents prior to immersion. Consequently, it is likely that cohesion in Blake and Gilman's Webster loam at $\theta = 0.31 \text{ m}^3 \text{ m}^{-3}$ continued to increase after the first two days, but since the aggregates were already stable against the mild disrupting force, further increases in cohesion were not detected by this procedure at this high water content. The decrease in rate at which cohesion develops as the soils contain less water (Blake and Gilman, 1970, in the range of $0.16 < \theta < 0.31 \text{ m}^3 \text{ m}^{-3}$) is supported by the curves in Fig. 2 which show that when soils have only about one molecular layer of water on their mineral surfaces, equivalent increases in cohesion take months instead of days to occur.

One possible type of bonding mechanism that would fit these observations would be selective precipitation of silica, CaCO_3 , and other slightly soluble solutes near particle-to-particle contacts where they can bond to both of the adjacent particles. At locations where such double bonding can occur for a solute molecular or ion, its free energy will be lower than the free energy of the same ion adsorbed on flat or convex surfaces. Consequently, solution near the sites with double bonding potential for a specific solution component will be depleted of that component. Diffusion will move components toward these zones of depletion from other regions of the solution which are adjacent to solid phases of the component which are more soluble. The rate at which such bonding develops would be highly dependent on the rate of diffusion in the system which would be much more rapid in the soils at higher water contents, but would persist at reduced rates as long as the water phase was continuous and the component was to some extent soluble therein. Since stability continued to increase when the soil had only one molecular layer of water on the surface, this explanation would require that components are somewhat soluble and mobile in a monomolecular water layer. Van Schaik et al. (1966) found the mobility of adsorbed Ca^{2+} in bentonite containing the equivalent of a monomolecular layer of water on all its surface to be about 3% of that of Ca^{2+} in bulk solution. CO_2 needed for CO_3 in CaCO_3 cementation could come via the gaseous phase. This 30-fold reduction in mobility may thus explain why increases in cohesion in this air-dry Portneuf soil takes months as compared to days in moist soils, and thus provides support for an explanation of the increasing cohesion involving migration of ions and molecules through the water phase to the bonding sites.

Types of binding involved in cohesion include direct attraction of atoms in adjacent solid particles discussed above and attraction via the water between the soil particles. Cohesional forces due to water may be estimated by consideration of Fig. 6, which represents two mineral spheres which are hydrated. Water is held by molecular attractions and diffuse layer osmotic forces in a thin layer, usually only a few molecular layers thick, on the convex surfaces. But near the con-

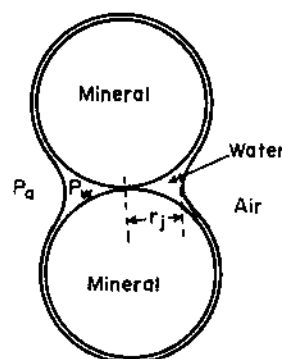


Fig. 6—Idealized particles held together by water.

tact point between the two spheres the surface tension of water and concave nature of the interface combine to hold a capillary wedge of water which can have thicknesses of hundreds or even thousands of molecular diameters, and in which there are pressures lower than the pressure in the air. There has been some question as to whether water has the tensile strength to sustain tensions that occur when pressures drop below zero in this capillary water, since observable volumes of water commonly nucleate when the pressure in the water goes below zero. However, Briggs (1950) demonstrated that water in 0.6-mm diam capillary tubes has sufficient tensile strength to withstand negative pressures or tensions up to about 26 000 kPa.

Two specific types of forces are active in the system shown in Fig. 6. The surface tension of water binds the two particles together with a force (N),

$$F_s = 2\pi r_j \sigma \quad [1]$$

where σ is the surface tension of the air-water interface in N/m and $2\pi r_j$ is the length (m) of that air-water interface acting to pull the particles together. The other force pulling these particles together involves pressure differences in the air and water phases. In the capillary wedges of water the pressure can be less than in the air phase. Integrating the pressures exerted on all sides of the spherical mineral particles, it is found that there is a net force due to phase pressure difference, pulling the particles together of

$$F_h = \pi r_j^2 (P_a - P_w) \quad [2]$$

where P_a and P_w are the pressures in pascals in the air and water phase respectively, and r_j is in meters, F_h is in newtons.

In bulk soils a gross estimate of the cohesion, F_{hs} ($\text{N/m}^2 = \text{Pa}$) is the phase pressure difference or suction, $P_a - P_w$, exhibited by the soil for water, times the portion, θ , $\text{m}^3 \text{ m}^{-3}$ of the soil volume occupied by the water phase, i.e.,

$$F_{hs} = \theta(P_a - P_w) \quad [3]$$

However, this will tend to be a high estimate of this force because a large portion of the soil water is not in the capillary wedges with $P_a - P_w = h_c$, the observable suction of the soil for water, but is adsorbed in thin films on convex and flat surfaces on and between platelets by forces involving ion hydration, dipole attraction, and osmotic forces associated with cations restrained in the diffuse layer.

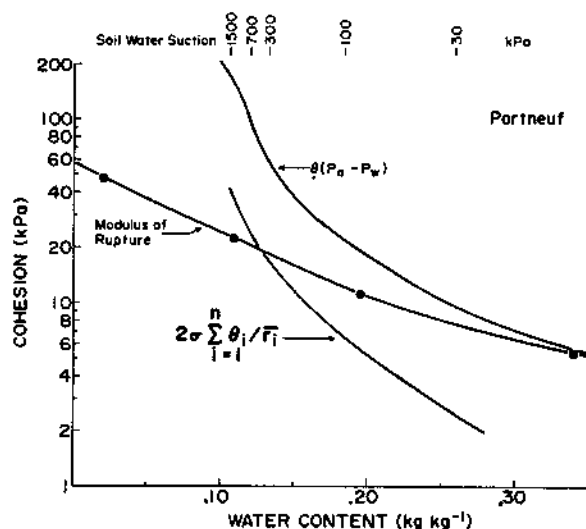


Fig. 7—Comparison of measured moduli of rupture of Portneuf to estimated cohesion due to surface and hydraulic tensions.

The cohesive surface tension force may be estimated by assuming that all pores emptied are spherical and have an air water interface around their circumference that exerts a surface tension. Then the contribution of a given pore of radius r_i to cohesion of the sample is, at a plane through the middle of that pore, $2\sigma\pi r_i$.

The number of N_i of such round pores in a given size range $r_i < r < r_{i+1}$ per unit cross sectional area of soil can be estimated from the fraction of the soil volume θ_i emptied of water between suctions related to r_i and r_{i+1} by the capillary equation. That is,

$$N_i = \theta_i / \pi \bar{r}_i^2 \quad [4]$$

where $\bar{r}_i = (r_i + r_{i+1})/2$ and θ_i values are taken from water retention characteristics of the type shown in Fig. 1. Following this procedure, this estimate of the cohesive force F_{ss} due to surface tension in the soil is

$$F_{ss} = \sum_{i=1}^n \frac{\theta_i}{\pi \bar{r}_i^2} 2\pi \bar{r}_i \sigma = 2\sigma \sum_{i=1}^n \frac{\theta_i}{\bar{r}_i} \quad [5]$$

Following the procedures indicated in Eq. [3] and [5] the cohesive forces due to hydraulic pressure and surface tension were estimated for the Portneuf and Billings soils from the water retention curves in Fig. 1 and are shown in Fig. 7 and 8, respectively.

These estimates of cohesive forces due to water indicate that their summation is large enough to account for the soil cohesion observed in the moduli of rupture measured for these soils. However, the assumptions inherent in these calculations make them overestimates of the cohesive forces due to water, particularly when there are internal flaws or microcracks in the samples, or water contents are low and a major portion of the remaining water is held by forces other than capillarity. Under conditions described for curves associated with the upright crosses in Fig. 4, Portneuf soil has greater moduli of rupture when it is moist than when it is oven dried showing that a substantial portion of the cohesion in this soil is due to water phase tension and surface tension associated with

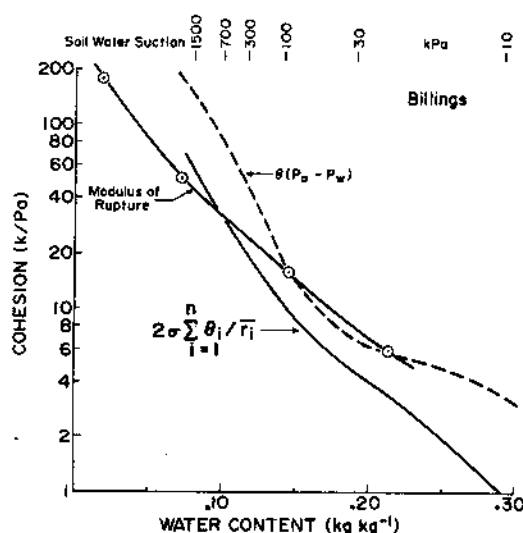


Fig. 8—Moduli of rupture of Billings soil and estimated cohesion due to surface and hydraulic tensions.

the air-water interface. Other factors in the more cohesive Billings soil always caused more cohesion when the soil was dry than when it was moist and thereby masked the cohesive effect of the water.

As long as the pressure in the air exceeds that in the water phase, water causes some cohesion of the soil. However, when the water pressure becomes equal to or greater than the air pressure and the soil becomes saturated, the water does not help soil particles to cohere, and freshly cultivated, weakly structured soils, such as the Portneuf, will slump or settle due to the force of gravity. The data in this study combined with those in the Utomo-Dexter and Blake-Gilman studies indicate that this slumping and consequent increase in densities that occur in the saturated zone of irrigated soils will be reduced if the aggregates formed by cultivation are allowed to cure for a few days before they are irrigated.

CONCLUSIONS

Cohesion of soils as measured by aggregate stabilities and moduli of rupture increases with time. Cohesional forces associated with water are in the range to be able to account for measured moduli of rupture in moist soils. However, high moduli of rupture of soils such as the Billings, when oven dry, indicate formation of solid phase bonds at particle-to-particle contacts. Increases of aggregate stabilities and moduli of rupture with time of storage or "curing" under air-dry conditions, indicate that migration of bonding components to strengthen these bonds continues even when there is as little as one molecular layer of water on the mineral surfaces.

These findings combined with those of other investigators suggest that soils will disintegrate and slump less if a few days are allowed for freshly cultivated soils to regain their solid phase cohesion before they are saturated by irrigation.

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